

AN OVERVIEW OF THE AIRBORNE ACTIVITIES DURING THE SOUTHERN  
OXIDANTS STUDY (SOS) 1995 NASHVILLE/MIDDLE TENNESSEE OZONE STUDY

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# An overview of the airborne activities during the Southern Oxidants Study (SOS) 1995 Nashville/Middle Tennessee Ozone Study

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**Abstract.** The cause and extent of elevated ozone levels which are often found during summer in the southeastern United States were the focus of the intensive Southern Oxidants Study (SOS) 1995 Nashville/Middle Tennessee Ozone Study. Six aircraft were extensively instrumented and were deployed in concert during the summer of 1995 from the Nashville Metropolitan Airport. This overview describes the capabilities of the deployed assets, and how their use was managed. Results from the measurements on individual aircraft and their interpretation are contained in the individual papers that follow.

## 1. Introduction

Elevated ozone concentrations have been observed at many locations in the southeastern United States [cf. Meagher *et al.*, this issue]. Understanding the atmospheric processes that determine these events is the focus of the Southern Oxidants Study (SOS). In order to gain this understanding, a comprehensive set of measurements, detailing the chemical and meteorological conditions for ozone photochemistry in the Southeast, were made at the surface and from airborne platforms during the summer of 1995. These measurements constituted the 1995 Nashville/Middle Tennessee Ozone study intensive. The study intensive was designed to address several science questions that still remain open even after extensive efforts in air quality research [cf. Cowling *et al.*, this issue]. This overview describes the research themes, the capability of the six deployed aircraft, their associated complement of instruments, and the deployment strategy that was followed for the integrated airborne operations during the study.

The science themes addressed by the aircraft measurements may be broadly categorized as scale, interactions, and exchange. The first theme addresses the spatial extent of ozone pollution and asks whether it is a regional or a local problem. For example, even though ozone can be elevated over large areas, especially during stagnant high-pressure periods [cf. Meagher *et al.*, this issue, Figure 1], it is still an open question how much ozone is produced locally and how much is

produced remotely and then transported to the locale of the exceedence. Remote formation in this sense includes the ozone formed during transport from precursors emitted elsewhere.

The second theme, interaction, addresses the question of what fraction of ozone observed at a specific location can be attributed to a particular source of ozone precursors located among a complex matrix of such precursor sources. Nashville and the surrounding region provide an ideal setting to address this question because Nashville is an isolated urban area set in a rural background with farming to the north and forested areas to the west-southwest. However, several large fossil fuel burning power plants with a wide range of pollutant emissions are imbedded in this rural background at various distances from the Nashville area. Under certain flow conditions the plumes of the power plants merge with each other and/or the urban plume; under other conditions they stay separate. Thus the impact of the interaction of power plant plumes, the urban plume, and the regional background can be investigated under a variety of conditions and in various combinations.

The third theme is exchange. One example is the exchange of air between the planetary boundary layer (PBL) and the lower free troposphere (LFT). Detrainment of highly polluted boundary layer air lowers the local impact by removing ozone precursors from the local photochemistry while redistributing the burden of anthropogenic pollution over large areas and to locales far removed from the pollution sources. Moreover, since the efficiency of ozone production depends nonlinearly on the concentration of ozone precursors [cf. Liu *et al.*, 1987] this mixing process may serve to modify the total ozone formation over a large region.

Other important exchange processes include those associated with the breakup of the nocturnal inversion, and transport by the nocturnal jet. The former process can have an important effect on the initial stages of daily O<sub>3</sub> production as the emissions trapped near the surface mix with the air aloft. The latter process, caused by the decoupling of the atmosphere from the surface during formation of the nocturnal inversion, may provide a significant but yet unappreciated and unquantified mechanism for regional transport and dispersion of local pollution.

Additional exchange processes that were addressed in the study included orographic forcing and air-surface exchange.

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The role of orographic forcing of PBL to LFT exchange was studied over the Appalachian mountains in eastern Tennessee/western North Carolina. The lofting of air as it passes over these mountains, coupled with the diurnally varying winds associated with mountain-valley drainage, may significantly alter the character of the background of ozone and ozone precursors depending on the direction of synoptic transport. Also investigated were air-surface exchange rates of sensible and latent heat, momentum,  $\text{CO}_2$ , and ozone. Surface deposition is an important component of the overall budget of tropospheric ozone.

This overview is intended to provide a brief description of the deployed aircraft, their capabilities, their instrumentation, and how these capabilities allowed the scientific objectives of the study to be addressed. A general description of aircraft operations and a brief discussion of the mentoring strategy used to determine the flight plans of the various aircraft on particular days are provided in order to avoid unnecessary repetition in the analysis papers that follow. The discussion of the intent of various flights from the perspective of a particular aircraft on a given day and the reporting of those results and their interpretation are contained in the individual papers that follow [e.g., Banta *et al.*, this issue; Gillani *et al.*, this issue; Jobson *et al.*, this issue; Kleinman *et al.*, this issue; Luke *et al.*, this issue; Ryerson *et al.*, this issue]. Detailed description of the coordinated deployment on single days and results from those flights will be presented in future papers.

## 2. Platforms and Instrumentation

The Nashville study was process-oriented where extensive airborne measurements were collected over a variety of ambient conditions and on various spatial scales. Six aircraft having a wide range of capabilities participated and contributed to accomplish the goals of the study. Two of these aircraft were equipped with a full array of instrumentation for study of  $\text{O}_3$  chemistry and had sufficient range and endurance to conduct measurements over large areas. The remaining four aircraft were devoted to more specialized tasks. A helicopter was used to obtain detailed chemistry measurements over the

urban area and in power plant plumes. A slow flying aircraft was used primarily to measure fluxes of  $\text{O}_3$ , heat, and momentum. The remaining two aircraft were equipped with instrumentation to remotely sense ozone and aerosols and were used primarily in a survey mode. The aircraft participating in the study are listed in Table 1 along with the affiliations of the groups providing the aircraft and their instrumentation. This discussion will briefly describe the aircraft and their instrument complements. The operational principles of the instruments used are provided in the separate manuscripts that discuss the results.

The deployed aircraft can be discussed in two groups: (1) Four of the aircraft carried instrumentation for a variety of in situ measurements; and (2) two aircraft had remote sensing instruments on board. To the first group belongs the National Oceanic and Atmospheric Administration (NOAA) WP-3D a large four-engine turboprop aircraft that is primarily used for hurricane reconnaissance and research. It has a ceiling of 7.6 km, a payload capacity of about 2700 kg, and an endurance of about 10 hours. At the typical research speeds of 370 km/h indicated air speed (IAS) (equal to 100 m/s), this translates into an operating radius of 1850 km. Over the last few years the Aeronomy Laboratory has developed a set of in situ instrumentation to study ozone photochemistry. Measurements of particular interest include the quantification of ozone, its precursors, and the by-products of the photochemistry that lead to ozone formation. Those by-products can be used as indicators or diagnostic species to help interpret comparisons made between measurements and model simulations. The most important by-products are the oxidation products of the precursors: the nitrogen oxides ( $\text{NO}_x = \text{NO} + \text{NO}_2$ ) and the volatile organic compounds (VOCs). Tracer measurements let us determine the sources of the compounds and the transport processes that distribute them throughout the atmosphere. Of course we need to know the meteorological parameters that pertain to chemistry and transport, too. The measurement package is described in Table 2.

The Department of Energy (DOE) Grumman G-1 was operated jointly by the DOE Pacific Northwest Laboratory (PNL) and Brookhaven National Laboratory (BNL). The G-1

Table 1. Participating Aircraft

	Aircraft Operator/Affiliation of PI	Payload
In situ:		
Lockheed WP-3D Orion	NOAA Aircraft Operations Center / NOAA	trace species for ozone
Grumman G-1	DOE Pacific Northwest Laboratory / Brookhaven National Laboratory	trace species for ozone photochemistry
DeHavilland DHC6 Twin Otter	NOAA Aircraft Operations Center / NOAA Air Resources Laboratory	fluxes, reduced set for ozone photochemistry
Bell 205 Helicopter	TVA Environmental Research Center	trace species for ozone photochemistry
Remote Sensing:		
Lockheed C-130 Hercules	NASA Wallops Island Flight Facility / Jet Propulsion Laboratory	vertical column measurements
CASA 212-200	Private vendor / NOAA Environmental Technology Laboratory	ozone and aerosol backscatter vertical profiles

**Table 2.** Instruments Carried Aboard the NOAA WP-3D Orion

Parameter	Time Resolution	Method	Detection Limit
Ozone (O <sub>3</sub> )	10 s	UV absorption	1 ppbv
Fast O <sub>3</sub> (FO <sub>3</sub> )	1 s	NO/O <sub>3</sub> chemiluminescence	0.2 ppbv
Carbon monoxide (CO)	10 s	NDIR	60 ppbv
Fast CO (FCO)	1 s	VUV resonance fluorescence	25 ppbv
Sulfur dioxide (SO <sub>2</sub> )	2 s	UV pulsed fluorescence	1 ppbv
Nitric oxide (NO)	1 s	NO/O <sub>3</sub> chemiluminescence	30 pptv
Nitrogen dioxide (NO <sub>2</sub> )	3 s	photolysis, NO/O <sub>3</sub> chemiluminescence	100 pptv
Total nitrogen oxides (NO <sub>x</sub> )	1 s	gold converter, NO/O <sub>3</sub> chemiluminescence	50 pptv
In situ VOCs	5 min/every 15 min	cryo collection, GC/FID	<10 pptv
Canister VOCs	5 min at selected times	canister sampling, GC/FID	<10 pptv
PAN	30 s/every 5 min	direct injection, GC/ECD	<5 pptv
PPN	30 s/every 5 min	direct injection, GC/ECD	<5 pptv
MPAN	30 s/every 5 min	direct injection, GC/ECD	<5 pptv
CH <sub>2</sub> O	3 min/every 3 min	coil-DNPH collection / HPLC	30 pptv
Peroxides (H <sub>2</sub> O <sub>2</sub> )	1 min	dual enzymatic, fluorimeter	30 pptv
Aerosol size distribution	1 s	laser sizing (FSSP 100)	0.5–8 µm
Aerosol size distribution	1 s	laser sizing (ASASP)	0.26–3 µm
Particle light absorption	1 min	light absorption at 550 nm: particle soot absorption photometer	1×10 <sup>-6</sup> inches/min min
Aerosol number concentration	1 s	droplet counter: condensation nuclei counter	0.0001 cm <sup>-3</sup> (0.01–1 µm)
Scat, bscat (450, 550, 700 nm)	1 s	integrating nephelometer	0.1–1 µm; accumulation mode
Aerosol composition	15 min/every 90 min	Teflon filter, IC analysis	~0.3–1 µm
UV radiation	1 s	300–400 nm, zenith and nadir	
Water vapor (H <sub>2</sub> O)	1 s	Lyman alpha absorption	
Air temperature	1 s	platinum thermistor	
Dewpoint/frostpoint	≤3 s	dew/frostpoint hygrometer	
Wind speed	1 s	derived	
Wind direction	1 s	derived	
Altitude	1 s	barometric	
Position	1 s	GPS	
Air speed	1 s	barometric	
Atmospheric reflectivity		C band and X band radar	

is a medium-size twin-engine plane with payload capacity of 1300 kg, a 6 hour endurance, a ceiling of 9 km, and research speed of typically 360 km/h IAS (100 m/s) and was flown with an unpressurized cabin limiting the operations to below 3.5 km. The G1 measurement package is also geared to study ozone photochemistry. The measurement package is described in Table 3. The majority of the G-1 flights were dedicated to documenting urban plume chemistry. Flights were also made to assess the variability of O<sub>3</sub> and O<sub>3</sub> precursors on subregional scales (i.e., 200 km), and to assess the effect of the breakup of the nocturnal boundary layer on O<sub>3</sub> formation chemistry.

The NOAA Twin Otter is a small, high-wing, twin-engine turboprop aircraft with an unpressurized cabin. The Twin Otter's ceiling is 7.6 km, and its payload capacity with full fuel is approximately 900 kg. Research cruising speed is typically

200 km/h IAS (56 m/s), and endurance with visual flight rules (VFR) reserves is approximately 4.5 hours; this translates into an operating radius of approximately 460 km. The Twin Otter carried a suite of fast response sensors for determination of air-surface exchange (turbulent flux) processes, complemented by instruments for the measurement of photochemically active trace gases and meteorological variables. The measurement package is listed in Table 4.

Another small aircraft, the Tennessee Valley Authority (TVA) Bell 205 helicopter has a payload capacity of 500 kg, a 2 hour endurance, a ceiling of 2.5 km, and research speed of typically 150 to 190 km/h IAS (40–50 m/s). The helicopter carried instruments for the in situ measurement of photochemically active trace gases. The measurement package is described in Table 5. With its high maneuverability the

Table 3. Instruments Carried Aboard the DOE Grumman G-1

Parameter	Time Resolution	Method	Detection Limit
Ozone (O <sub>3</sub> )	20 s	UV absorption	5 ppbv
Carbon monoxide (CO)	50 s	NDIR	20 ppbv
Sulfur dioxide (SO <sub>2</sub> )	<10 s	pulsed fluorescence	200 pptv
Nitric oxide (NO)	<10 s	O <sub>3</sub> chemiluminescence	10 pptv
Nitrogen dioxide (NO <sub>2</sub> )	<10 s	O <sub>3</sub> chemiluminescence	22 pptv
Total nitrogen oxides (NO <sub>x</sub> )	<10 s	O <sub>3</sub> chemiluminescence	100 pptv
VOCs	30 - 60 s	canister collection/GC-FID	
Temperature	<10 s	platinum resistance	N/A
Dewpoint	<10 s	chilled mirror	N/A
Position			
Altitude	<10 s	capacitive transducer	N/A
Latitude	<10 s	GPS	N/A
Longitude	<10 s	GPS	N/A
Static pressure	<10 s	capacitive transducer	1 mb
Ultraviolet radiation	<10 s	pyranometer	N/A
PAN	7-10 min	GC/ECD	10 pptv
Formaldehyde	5 min	scrubber/IC	30 pptv
Glycoaldehyde	5 min	scrubber/IC	20 pptv
Glyoxal	5 min	scrubber/IC	20 pptv
Methylglyoxal	5 min	scrubber/IC	20 pptv
Pyruvic acid	5 min	scrubber/IC	20 pptv
Methylhydroperoxide	1 min	Fenton/peroxidase	100 pptv
Hydroxymethylhydroperoxide	1 min	Fenton/peroxidase	100 pptv
Hydrogen peroxide	1 min	Fenton/peroxidase	50 pptv
Total peroxide	1 min	Fenton/peroxidase	30 pptv
Particles size distribution	<10 s	light scattering (PCASP)	< 1 cm <sup>-3</sup>
Particles size distribution	<10 s	light scattering (FSSP)	< 1 cm <sup>-3</sup>

helicopter is especially well suited to fly close to point sources and investigate plume evolution close in.

Finally, two of the aircraft were dedicated to profiling measurements. The CASA 212-200 contracted from a private vendor is a small high-wing cargo aircraft with a rear cargo door and it has about a 4.5 hour flight endurance. The CASA was modified to allow the installation of the NOAA-Environmental Technology Laboratory (ETL) light detecting and ranging (LIDAR) measurement package whose capabilities are described in Table 6. The downward looking LIDAR system

measures the vertical distributions of ozone and aerosol backscatter below the flight path. Ozone concentrations are derived from the measurement of differential absorption signals. The aircraft usually flew at 3000 m above mean sea level (msl), while the local surface was approximately 200 m msl. The final LIDAR data are available as 8 s averages corresponding to 520 m horizontal resolution at the 65 m/s flight speed. The data are, furthermore, vertically averaged to a resolution of 90 m. The data were recorded though with higher time resolution which allows analysis (e.g., power plant

**Table 4.** Instruments Carried Aboard the NOAA DeHavilland DHC6 Twin Otter

Parameter	Time Resolution	Method	Detection Limit
Ozone (O <sub>3</sub> )	10 s	UV absorption	2 ppbv
Carbon monoxide (CO)	20 s	NDIR/GFC	20 ppbv (30 s avg.)
Sulfur dioxide (SO <sub>2</sub> )	10 s	pulsed fluorescence	0.3 ppbv (30 s avg.)
Nitric oxide (NO)	2 s	Ozone (O <sub>3</sub> ) chemiluminescence	30 pptv (30 s avg.)
Nitrogen dioxide (NO <sub>2</sub> )	2 s	photolysis cell	200 pptv (30 s avg.)
Total nitrogen oxides (NO <sub>y</sub> )	2 s	molybdenum converter	300 pptv (30 s avg.)
Canister VOCs	40-75 s	canister/GC/MS (Georgia Tech)	
Carbon dioxide (CO <sub>2</sub> )	0.3 s	IR absorption	0.3 ppbv
Water (H <sub>2</sub> O)	0.3 s	IR absorption	0.05 mbar
Fast ozone (O <sub>3</sub> ) (flux)	0.05 s	coumarin chemiluminescence	0.1 ppbv (0.2 s avg.)
CO <sub>2</sub> (flux)	0.05 s	IR absorption / LICOR	0.3 ppbv
H <sub>2</sub> O (flux)	0.05 s	IR absorption / LICOR	0.05 mbar
Temperature	0.1 s		± 0.05° C
Dewpoint	1 s	chilled mirror	
Ultraviolet radiation	0.5 s	Eppley TUVR (290-385 nm)	± 5 W/m <sup>2</sup>
Net radiation	30 s	REBS different thermopile	± 5 W/m <sup>2</sup>
Wind speed/wind direction	0.025 s	pressure sphere anemometer/ GPS	± 0.1 m/s
Turbulence	0.025 s	pressure sphere anemometer/ GPS	± 20 W/m <sup>2</sup>
Winds and aircraft attitude	0.1 s	TANS vector GPS	± 0.2 m/s
Position	0.05 s	GPS	± 3 m
Altitude	0.05 s	barometric and radar and GPS	
Aircraft velocity	0.05 s	GPS	± 3 cm/s

plumes) with more spatial detail. Design and specification of subcomponents (overlap of outgoing LIDAR beam and field-of-view of the optics; large though limited range of backscatter amplitude that can be recorded) limit the availability of useful data from approximately 800-1000 m below the aircraft to 100-200 m above ground level depending on terrain and cloud cover. Since the UV and visible radiation used for the LIDAR does not penetrate clouds, there are no data below clouds. The aircraft operated above the mixed layer and provided profile information to the surface with primary focus on mapping the Nashville urban plume and providing

additional information on power plant plume structure and mapping regional ozone levels to provide a context for interpretation of the detailed chemical measurements made by the other aircraft.

The second remote-sensing aircraft, the National Aeronautics and Space Administration (NASA) Wallops Hercules C-130, is a large four-engine turboprop designed as a military transporter with flight characteristics similar to the WP-3D. The plane carried the Airborne Emission Spectrometer (AES), a nadir viewing infrared Fourier transform spectrometer with 0.1 cm<sup>-1</sup> spectral resolution. The instrument measures the

**Table 5.** Instruments Carried Aboard the TVA Bell 205 Helicopter

Parameter	Time Resolutions	Method	Detection Limit
Nitric oxide (NO)	1 s	chemiluminescence	0.5 ppbv
Nitrogen dioxide (NO <sub>2</sub> )	1 s	photolysis and chemiluminescence	0.5 ppbv
Total nitrogen oxides (NO <sub>y</sub> )	1 s	gold tube and NO/O <sub>3</sub> chemiluminescence	0.5 ppbv
NO <sub>y</sub> * (NO <sub>y</sub> - [gas and aerosol nitrate])	1 s	gold tube and NO/O <sub>3</sub> chemiluminescence	0.5 ppbv MDL - Nylasorb filter
Ozone (O <sub>3</sub> )	10 s	UV absorption	1 ppbv
Fast ozone (FO <sub>3</sub> )	1 s	NO/O <sub>3</sub> chemiluminescence	2.0 ppbv
Carbon monoxide (CO)	5 s	gas filter correlation	40 ppbv
Sulfur dioxide (SO <sub>2</sub> )	5 s	pulsed fluorescence	1 ppbv
Canister VOCs	~30 s	canister	MDL varies with compound
Total peroxides	~20 s	enzyme reaction / fluorimetric	0.5 ppbv
Hydrogen peroxide (H <sub>2</sub> O <sub>2</sub> = total - organic)	~20 s	dual enzyme / fluorimetric	0.5 ppbv
Temperature	5 s	platinum RTD	
Relative humidity	5 s	capacitance	
Altitude	5 s	barometric (Piezo cell)	0.3 mbar precision
Position	5 s	LORAN	

atmospheric and surface spectrum at wavelengths between 5 and 15.6  $\mu\text{m}$  to provide column amounts of a wide range of atmospheric constituents and temperature (Table 7). The SOS flights focused on O<sub>3</sub>, H<sub>2</sub>O vapor, CO, and temperature. All C-130 flights were flown in a standard search pattern, covering roughly a 1° by 1° area at an altitude of 6.1 km.

When utilizing the measurements made aboard these aircraft, one needs to consider the measurement characteristics coupled with the flight characteristic of the sampling platform. On a measurement platform moving at typical research aircraft speeds of 50–100 m/s, transects of power plant plumes and airborne flux studies require instruments with high time

resolution ( $\geq 1$  Hz). However, depending on the use of the data and the speed of the aircraft, measurements made on longer timescales may be quite useful for determining average concentrations over extended segments of the flight.

While regional surveys do not pose especially severe demand on instrument capabilities, it is desirable that the platform has sufficient endurance/range. Although they could accomplish a variety of flight objectives, two in situ aircraft, the NOAA Orion WP-3D and the DOE BNL/PNL Grumman G-1, had the range and speed to undertake measurements over a wide region within one flight. Only the WP-3D made forays to the north, outside of the immediate study area

**Table 6.** Instruments Carried Aboard the NOAA CASA 212-200

Parameter	Time/Space Resolution	Method	Detection Limit
Ozone (O <sub>3</sub> )	3–8 s / 200–520 m horizontal, 15 m vertical	differential absorption LIDAR	5 ppbv
Aerosol backscatter	3–8 s / 200–520 m horizontal, 15 m vertical	LIDAR	$5 \times 10^{-7} \text{ m}^{-1} \text{ sr}^{-1}$

Table 7. Measurement Suite of NASA C-130 Hercules

Parameter	Sample Time / Vertical Resolution	Method	Detection Limit
Ozone (O <sub>3</sub> )	30 s / 3 km	IR remote sensing	
Carbon monoxide (CO)	30 s / 6 km	IR remote sensing	
Methane (CH <sub>4</sub> )	30 s / 6 km	IR remote sensing	
Water (H <sub>2</sub> O)	30 s / 2 km	IR remote sensing	
Nitrous oxide (N <sub>2</sub> O)	30 s / 6 km	IR remote sensing	
Sulfur dioxide (SO <sub>2</sub> )	30 s / 6 km	IR remote sensing	technique experimental
Nitric acid (HNO <sub>3</sub> )	30 s / 6 km	IR remote sensing	technique experimental
Temperature	30 s / 3 km	IR remote sensing	
Surface brightness temperature	30 s	IR remote sensing	

(Nashville/middle Tennessee), into the farmlands of Illinois and Indiana to contrast that region to the middle Tennessee main study area.

### 3. Aircraft Operation Under the Mentor Concept

The broad objectives of the Nashville study were outlined by the SOS Science Team. A subset of these scientists were selected to be mentors to design and represent individual experiments during the program. The SOS Science Team in consultation with the mentors identified five experimental objectives. These objectives and their mentors are listed in Table 8. Each of the experimental objectives is described briefly below. The mentor concept proved to be particularly useful for day-to-day planning during the large-scale cooperative efforts undertaken during the 1995 Nashville/Middle Tennessee Ozone Study. The mentors were responsible for designing the aircraft measurements and worked together as a planning team during the program to convert the experimental objectives into a set of flight plans that best used the aircraft and surface measurement resources under the prevailing set of conditions. Prior to this study the mentors developed a series of "game plans" that used

combinations of the six available aircraft to accomplish the five experimental objectives. In most cases, there was sufficient overlap of measurement requirements that several experimental objectives could be addressed with a given set of flight plans.

The mentors were responsible for coordinating and overseeing the implementation of the plan in the field. Prior to the deployment, as a matter of judicious use of the aircraft resources, it was planned that each aircraft would fly no more frequently than every other day. Decisions concerning which experiment(s) would be serviced and which aircraft would fly were made by the mentor team. Critical input to this decision-making included weather forecasts provided by the meteorological support team, hourly region wide surface ozone distributions recorded by 108 stations belonging to several ozone monitor networks and regional surface chemistry data available in real time from six specifically instrumented sites (level 1, 2 networks; level 1: ozone only; level 2: ozone, some additional trace gases and meteorology [Meagher *et al.*, this issue]). Preliminary flight plans were submitted to the Nashville and Memphis Federal Aviation Administration (FAA) offices by 1500 LT the day prior to the proposed flights, and modifications, if necessary, were submitted the following morning after the daily mentor team meeting. Under

Table 8. Mentor Themes

	Mentor
Urban plume studies	Peter Daum and Larry Kleinman, BNL
Power plant plume studies	Noor Gillani, TVA
Subregional characterization	Robin Dennis, NOAA/EPA
Regional studies	Michael Trainer, NOAA-AL
Aircraft intercomparisons	Jim Meagher, TVA and Gerd Hübler, NOAA-AL

particularly favorable weather conditions, decisions were frequently made to fly on successive days (see Table 9). Mission debriefings and review of preliminary data by study scientists occurred in daily mentor team meetings and/or during the twice-a-week General Meetings open to all study participants. The mentors were also responsible for initiating and coordinating subsequent data analyses.

## 4. Study Objectives

### 4.1. Urban Plume Studies

The overall objective of these studies was to examine the rate and efficiency of ozone formation in the Nashville urban plume over a range of processing conditions. Underlying objectives were to gain insight with regard to how processing of Nashville emissions to form  $O_3$  changes according to the composition of the background air as determined by processing history and meteorology, and such factors as boundary layer height and wind speed which determine the rate at which the Nashville emissions are diluted and advected downwind. The influence of power plant plume emissions on the rate and amount of  $O_3$  formed was of particular interest.

### 4.2. Power Plant Plume Studies

Fossil fuel power plants are known to contribute significantly to the regional  $NO_x$  emissions. These studies were designed to

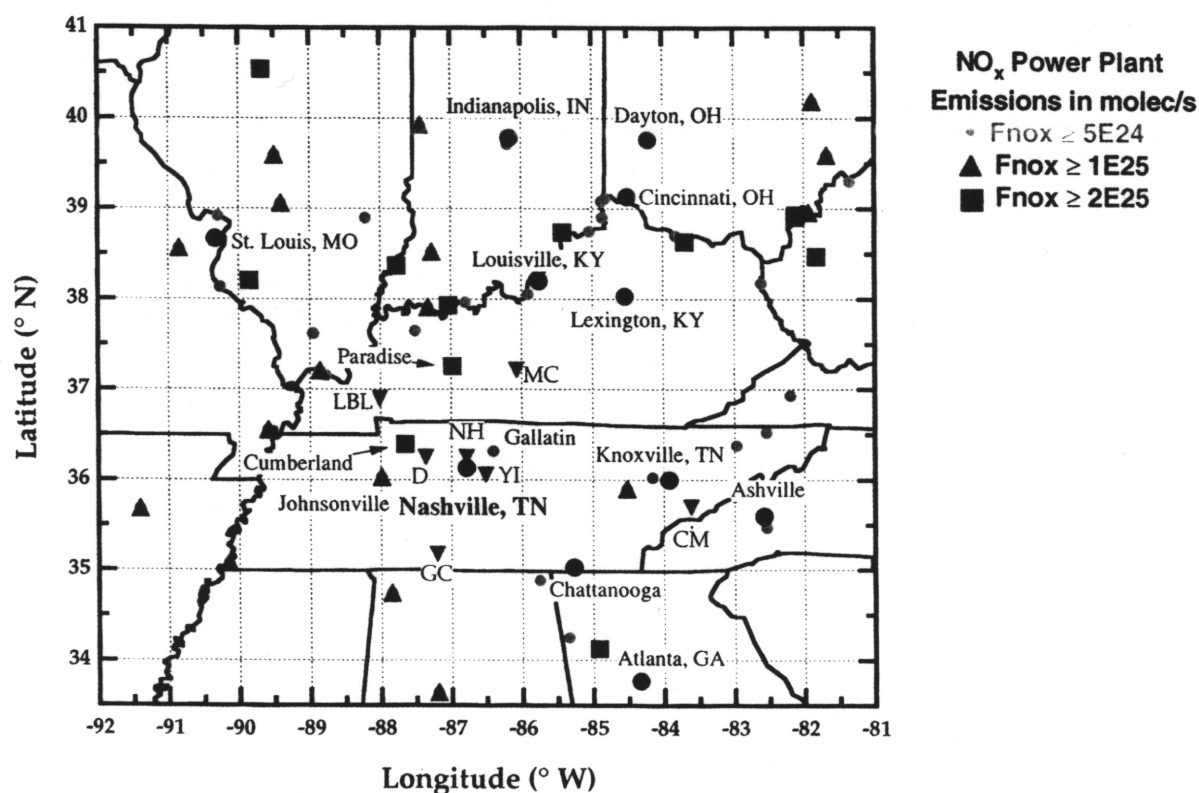
determine how the primary  $NO_x$  and  $SO_2$  emissions from the plants were dispersed and chemically processed, and to investigate the evolution of  $O_3$ ,  $H_2O_2$  and other short-lived photochemical species in these plumes. The experiments also explored plume-background and plume-plume interactions.

### 4.3. Subregional Characterization

These measurements were designed to examine how the interaction of power plant plumes or of urban and power plant plumes was manifested in local (urban or rural) to region-wide ozone accumulation. A key influence on local photochemical production and accumulation is the regional and local meteorology. The measurements were designed to contrast precursor species, oxidation products and composition, and  $O_3$  accumulation for a variety of meteorological conditions. The measurements were also designed to examine the local variability in chemical conditions and species composition that could influence the urban-rural exchange of ozone and ozone precursors.

### 4.4. Regional Studies

Aircraft measurements were extended to the north up into the farmlands of Illinois and Indiana, crossing the industrial belt



**Plate 1.** The southeastern United States with selected metropolitan areas (large solid circles) and major  $NO_x$  point sources (small solid circles, solid triangles, solid squares) according to the 1985 EPA emission inventory. The size and shape of the symbol indicates the magnitude range of the emission source. Also included are the location of the level 2 & 3 sites as inverted triangles; level 2: Cove Mountain (CM), Dickson (D), Downtown Nashville, Land between the Lakes (LBL), Giles County (GC), Mammoth Cave (MC); level 3: New Hendersonville (NH), Youth Incorporated (YI).

Table 9. Aircraft Flight Schedule

	Bell 205	CASA	C-130	G-1	WP-3D	Twin Otter
21 June	1315-1500 1515-1715				1300-1745	
23 June	1330-1545 1600-1800					0845-1115
24 June	1245-1445 1500-1730	1230-1645		1145-1415	1030-1515	
25 June						0830-1315
26 June		1300-1800			1100-1700	
27 June	1200-1400 1530-1730	1200-1615		1145-1600		1115-1530
28 June				1245-1730		1045-1515
29 June	1230-1430 1445-1645 1700-1830	1245-1700		1245-1630	1245-1830	1300-1715
1 July					1200-1830	
2 July	1100-1300 1415-1630	1230-1615		1145-1600		1300-1800
3 July		1000-1430		1200-1615	0600-1215	1045-1515
6 July				1545-1845	1600-1930	
7 July	0800-1030 1045-1300 1330-1500 1515-1630	0930-1400	1100-1645	1245-1630	1200-1830	0845-1345
8 July	1100-1200 1315-1515 1530-1645	1000-1530	0930-1530	1145-1545	1130-1700	0800-1230
10 July	1015-1215 1230-1430 1445-1630				1000-1600	1100-1500
11 July	1000-1200 1330-1530 1545-1745	1000-1415	0945-1530	1300-1600	1000-1630	1100-1530
12 July	1000-1200 1400-1600 1615-1730	0700-1100 1200-1600	0930-1530	0700-1100		0700-1130
13 July	1400-1600	1020-1430	1315-1815	1015-1445	1045-1615	
14 July					1000-1700	1300-1715
15 July	1000-1100 1215-1415	1000-1400	0915-1430	0945-1315		1015-1430
16 July	1230-1400 1415-1615 1645-1845	1000-1400				
17 July	1015-1215 1230-1415	0900-1330		0945-1315	1030-1630	
18 July	1445-1600	0900-1315		0945-1400		1100-1545
19 July	0930-1130 1145-1330 1400-1545	0930-1345		0945-1315	0630-1230	0800-1230
20 July	0800-1000 1030-1230	0800-1215		0730-1130	1000-1600	

Actual times were rounded to nearest quarter hour.

in the Ohio river valley to provide a context for the measurements in and around Nashville and to contrast the rural and more industrialized areas and different emission sources. For example, the midwestern region lies downwind of major metropolitan centers (St. Louis, Chicago) and contains several medium size urban centers such as Indianapolis to the north and Nashville to the south. There are a variety of large industrial point sources embedded into rural environments that emit substantial  $\text{NO}_x$ . In the rural areas, biogenic emissions also may play important roles, but the nature of these roles may depend strongly on location. To the north of Nashville lie intensely cultivated farmlands that may have significant  $\text{NO}_x$  emissions from soils but greatly reduced biogenic nonmethane hydrocarbon emissions. By contrast, forested areas, especially to the west of Nashville, have much larger biogenic NMHC emissions.

#### 4.5. Aircraft Intercomparisons

Early in the planning process, the need to intercompare measurements from the various aircraft was recognized. The motivation for these intercomparisons was to identify problems early in the program so they could be fixed, and to establish a basis for the compatibility of the data, so that data from multiple platforms could be combined during analysis with a knowledge of the uncertainties or biases in the measurements from individual platforms. It was clear, however, that not every aircraft could engage in multiple in-flight intercomparisons with all other aircraft because some have significantly different flight characteristics than others and because of limitations on the number of flight hours available for the program. Therefore it was decided to pair aircraft with similar flight characteristics for side-by-side intercomparison and to have the remote sensing aircraft overfly the intercomparing aircraft when weather conditions permitted. Several intercomparisons were planned and executed during the program. These intercomparisons consisted of multialtitude side-by-side flight legs of 10–15 min duration and a vertical profile. The vertical profiles were spaced by a distance of several miles.

Although the mentors designed detailed flight plans to address specific scientific issues, in practice there was much synergism in construction of flight plans for individual days. For example, flights to study the Nashville urban plume were often combined with flights to study power plant plumes because such flights would frequently intercept both kinds of plumes. Further, since both power plant and urban plume studies require upwind sampling to determine background concentrations, these flights were also used to characterize regional and subregional variability. Similarly, the data gathered during each of the intercomparison flight legs contributed to the overall data set, showing the local and day-to-day variability, and since the intercomparisons always involved multiple flight legs within and above the PBL, these flights also provided data on the contrast of the chemical composition between the PBL and the LFT.

### 5. Synopsis of Deployment

Since Nashville and the surrounding middle Tennessee region were the focus of the study, most of the flights were conducted in close proximity to the metropolitan area. In general, four power plants (Cumberland, Gallatin,

Johnsonville, and Paradise) by their location may impact this area depending on the wind flow. The power plants vary not only in size of their power production, and emissions but also, due to different fuel sources and installed emission controls, in the emission ratios of the primary pollutants  $\text{NO}_x$  to  $\text{SO}_x$  [cf. Ryerson *et al.*, this issue]. The locations of these plants along with a variety of other point sources in the area are shown in Plate 1. Upwind of Nashville under typical prevailing flow lie the power plants of Johnsonville and Cumberland at about 80 to 100 km to the west. Much closer to the city on the northeast side is Gallatin which has also the smallest  $\text{NO}_x$  emissions of the four plants. Paradise, one of the larger power plants, is located about 150 km almost due north in Kentucky. Flight legs upwind of these point sources were made to determine the regional inflow levels of oxidants and their precursors. The different aircraft groups developed and executed various flight profiles to study the chemistry of the Nashville urban plume, the power plant plumes, and their interactions.

Continuous ground-based chemical composition measurements were made at eight sites in the Tennessee region during the study (see Plate 1; level 2 sites: Cove Mountain, Tennessee, Dickson, Tennessee, Downtown Nashville, Tennessee, Giles County, Tennessee, Land between the Lakes, Kentucky, Mammoth Cave, Kentucky; level 3 sites: New Hendersonville, Tennessee, Youth Incorporated, Tennessee [cf. Meagher *et al.*, this issue]). The level 2 sites recorded ozone, sulphur dioxide, and carbon monoxide. Measurements of nitric oxide, total reactive nitrogen oxides ( $\text{NO}_y$ ) and meteorological parameters were also made continuously, while VOCs were collected in cans only at midday for 1 hour composites. A more complete set of photochemical species was measured at the level 3 sites. These included PAN, nitric acid, organic nitrates, and frequent in situ measurements of light and heavy hydrocarbons. To relate the aircraft and the ground measurements, flightplans were often designed to cross over the ground sites or to include vertical profiles near them. The two northernmost ground sites are Land between the Lakes (LBL) and Mammoth Cave (MC), both in Kentucky to the NW and NE of Nashville, respectively, while the Giles County (GC), Tennessee, site lies south of Nashville. The easternmost site Cove Mountain (CM), Tennessee, is located in the Appalachian Mountains. The others (Dickson (D), New Hendersonville (NH), and Youth Incorporated (YI)) are located closer to Nashville. In addition to the ground level chemical and meteorology measurements, boundary layer radar profiler measurements were made at Dickson west of Nashville and Youth Incorporated in the southeast of Nashville. Hence these flights covered the area of the boundary layer profiler network with stations at Land between the Lakes, Giles County, and Mammoth Cave along with the two sites close to Nashville (Dickson, New Hendersonville). The flights were all launched between June 20 and July 21, 1995 (Table 9). Aside from the C-130 Hercules, all aircraft flew throughout this time window.

Although most of the flights were conducted during the middle of the day (Table 9) to catch the photochemically most active period, the WP-3D, the G-1, and the Twin Otter each launched two, and the CASA launched one, early morning flights to study the impacts and the breakup of the nighttime inversion. In this region, the effects of the nocturnal inversion can be manifested in two very different ways: (1) emissions in the urban areas may accumulate during the night, below the inversion and be later redistributed when the nocturnal inversion breaks up in the morning; while, (2) nighttime

emissions from tall stacks of power plants may be released above the inversion into the free troposphere allowing them to be dispersed more widely over the region.

The availability of multiple aircraft with redundant capabilities allowed the deployment of the aircraft in a coordinated way so that even when several of the aircraft stayed close to Nashville, another aircraft (mainly the WP-3D) could investigate a larger area, which meant essentially extending the areal coverage. Aircraft with the same capabilities were sometimes scheduled to fly on alternate days and thus extended the coverage in time (for deployment schedule, see Table 9). Otherwise, such coverage would have been impossible due to the operational limitations (aircraft crew rest, maintenance, etc.). Through staggered deployment, a longer portion of the day was covered.

A synopsis of the flights for the six aircraft is shown in Figure 1. It shows the areas covered by each aircraft overlaid on the map of the greater Tennessee region with its pollution sources (same as Plate 1). The covered areas overlap with Nashville, located in the center of the area, being the focus. The extent of coverage is only partially a reflection of the aircraft range. For instance, the operating domain of the TVA Bell helicopter was frequently extended through refueling in route, while the DOE G-1 endurance was exploited by repeating a sampling pattern in one flight more than twice. Plate 2 contains composites of all the individual flight tracks and indicates that the area around Nashville/Middle Tennessee was covered most intensively.

A composite of all the individual flight tracks of the WP-3D in 1995 is shown in the top left panel of Plate 2. The frequency distribution of the number of measurements taken in various altitude bins thus reflecting the time spent at those altitudes is shown in Figure 2. The WP-3D spent more than half (56%) of the flight time at altitudes below 1000 m within the planetary boundary layer, which was the focus of the 1995 study. With its extended range capabilities, the NOAA WP-3D made several forays outside the area immediately adjacent to Nashville. Although most of the measurements were made around Nashville, the range of the aircraft allowed measurements to be made of the atmospheric composition over the farmlands of Illinois and Indiana, the more industrialized Ohio river valley, and the surroundings of the Cincinnati, Indianapolis, and Dayton metropolitan areas, thus contrasting as mentioned above the region of the Midwest with significant biogenic  $\text{NO}_x$  emissions from the soils to the forest regions in Tennessee, which exhibit significant biogenic hydrocarbon emissions. One additional flight to the east crossed the Appalachian Mountains providing the opportunity to contrast middle Tennessee and the Carolinas. Furthermore, on several flight legs above the Appalachians we looked for signatures of orographically induced exchange between the PBL and the LFT.

Information concerning all the flights of the DOE G-1 in 1995 is also shown in Plate 2 and Figure 2. Most of the G-1 flights focused on examining  $\text{O}_3$  production in the Nashville urban plume. Typically, such flights consisted of multialtitude, crosswind transects both upwind of the urban area and at several distances downwind. The locations of the downwind transects were chosen so that the urban plume was sampled at different stages of processing. The concept was to examine how quantities, such as the  $\text{O}_3$  formation rate and efficiency, and the parameters that control these quantities,

change as the urban plume advects downwind and mixes with the surrounding atmosphere. Other flights focused on characterizing the regional area surrounding Nashville. The purpose of such flights was to provide a context for interpretation of the Nashville plume data and to provide modelers with information on the subgrid scale variability of trace gas concentrations. Regardless of their purpose, all flights included at least one vertical profile from ~500 ft above ground level (AGL) to 10,000 ft msl to determine boundary layer height and to document the vertical distribution of trace gas and aerosol concentrations. An effort was made to conduct these vertical profiles over a SOS surface site to provide a connection between the surface measurements and the measurements made aloft.

The composite ground tracks of the NOAA Twin Otter flights in 1995 are shown in Plate 2. Figure 2 indicates the altitudes covered by the aircraft from near the surface to about 3000 m. Most of the flights were in the immediate vicinity of Nashville. These flights were intended to determine loss of ozone due to surface deposition in the area. The aircraft also made profiles around Nashville and the large point sources to the northwest to ascertain the distribution of  $\text{O}_3$  and  $\text{O}_3$  precursors though the boundary layer in the area. One longer flight was made to the east of Nashville to make a comparison with ground-based measurements near Oak Ridge, Tennessee.

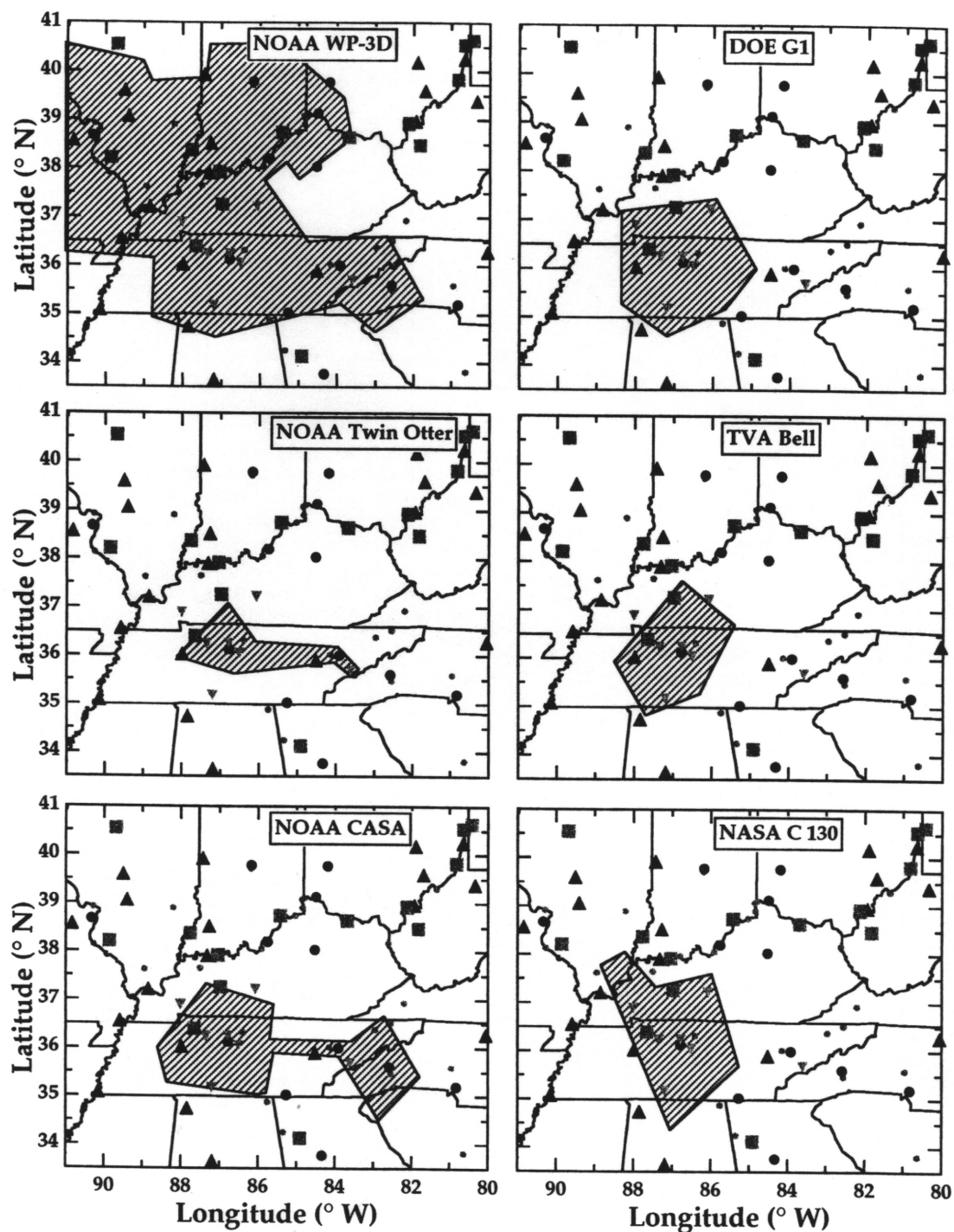
The TVA Bell helicopter made profiles and transects of the Nashville urban plume and surrounding power plant plumes measuring the distribution of  $\text{O}_3$  and  $\text{O}_3$  precursors (Plate 2). The unique maneuverability and control provided by this airborne platform also allowed the helicopter to do profiles and transects over the central city. Profiles were also made over the level 2 ground sites during the course of the study.

The composite flight tracks of the NOAA CASA 212 and the NASA C-130 are added to Plate 2. Both aircraft sampled the atmospheric composition between the optical instruments carried aboard the aircraft and the surface and maintained nearly constant altitudes through the duration of the flight. During this study those altitudes were typically 3 km for the CASA and 6.1 km in the case of the C-130. In the case of the C-130, the flight path was designed to scan an area of about 100 km by 100 km centered on Nashville with the main axis perpendicular to the main wind direction.

## 6. Summary

The defining feature of the 1995 Nashville/Middle Tennessee Study of SOS was the coordinated use of six aircraft. The wide regional coverage provided by these aircraft measurements allows evaluation and analysis of the local composition of the atmosphere around Nashville in a much wider regional context. However, in order to accomplish the science objectives proposed for the study, the deployment of these aircraft required preplanned flight scenarios involving combinations of these aircraft. The preplanned scenarios for each objective were devised by the aircraft mentors. These scenarios depended heavily on identifying the most favorable meteorological conditions for the goals of that scenario to be accomplished. Discussion among the mentors identified the similarities between flight scenarios. Hence it was recognized that certain meteorological conditions would allow scenarios to be combined and multiple objectives to be accomplished.

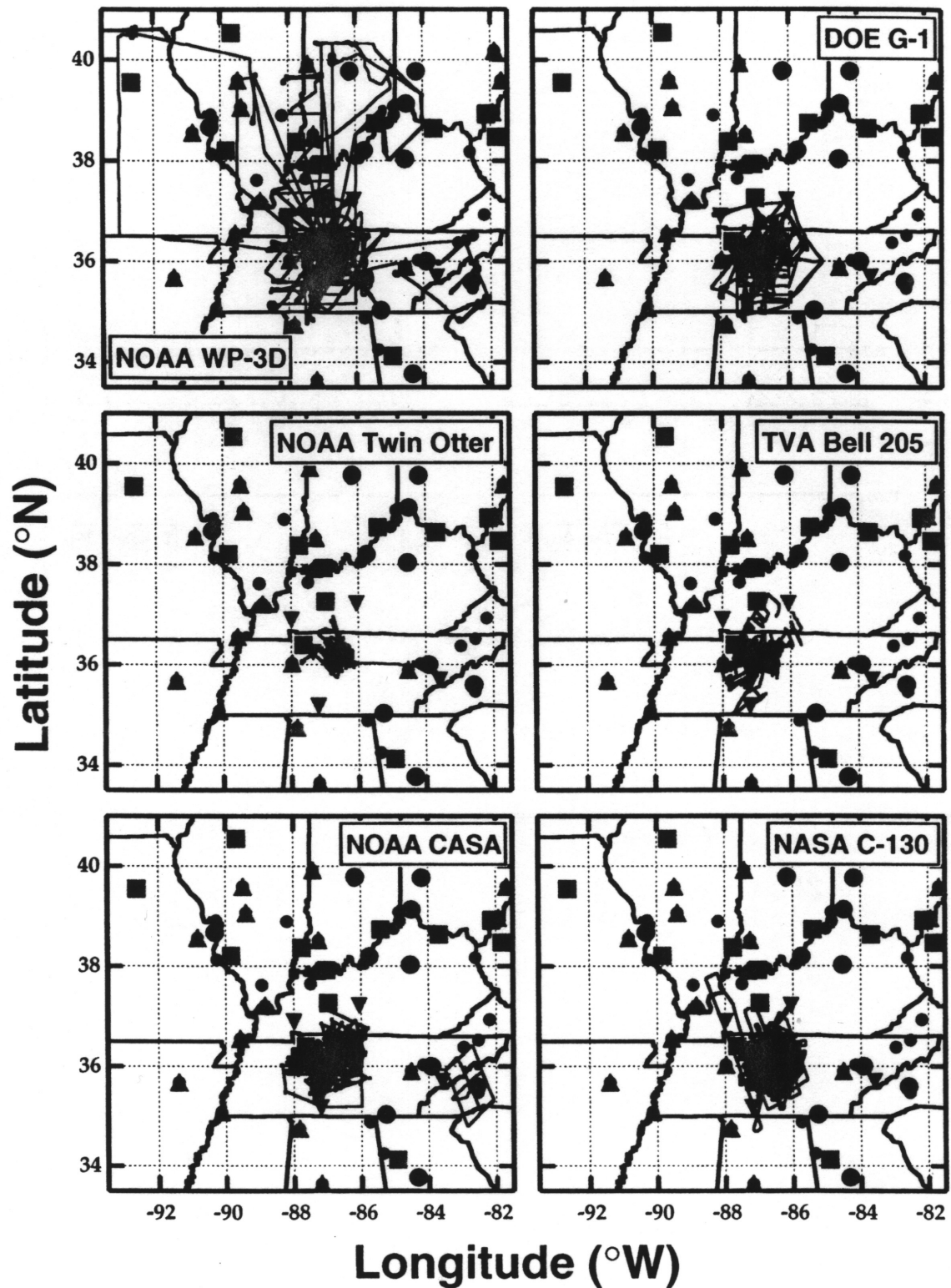
During the study these coordinated flight scenarios were selected each day on the basis of: (1) the previous day's



**Figure 1.** Area covered by the flights of the NOAA WP-3D, DOE G1, NOAA Twin Otter, TVA Bell 205 Helicopter, CASA 212, and NASA C-130 Hercules.

noon-time reading from the level 1 ground sites; (2) the early morning soundings from the radar profiler network and ozone sondes releases; (3) the prevailing meteorology throughout the region and the forecasts; and (4) the number of flight hours available and the number of flights accomplished for each

science objective. In this way, the critical chemical measurements made aboard these aircraft were compared to allow uncertainties in these measurements to be evaluated. Details of the evolution of urban and power plant plumes were investigated. Finally, the subgrid-scale perturbation in the



**Plate 2.** Composite flight tracks of the NOAA WP-3D, DOE G1, NOAA Twin Otter, TVA Bell 205 Helicopter, CASA 212, and NASA C-130 Hercules.

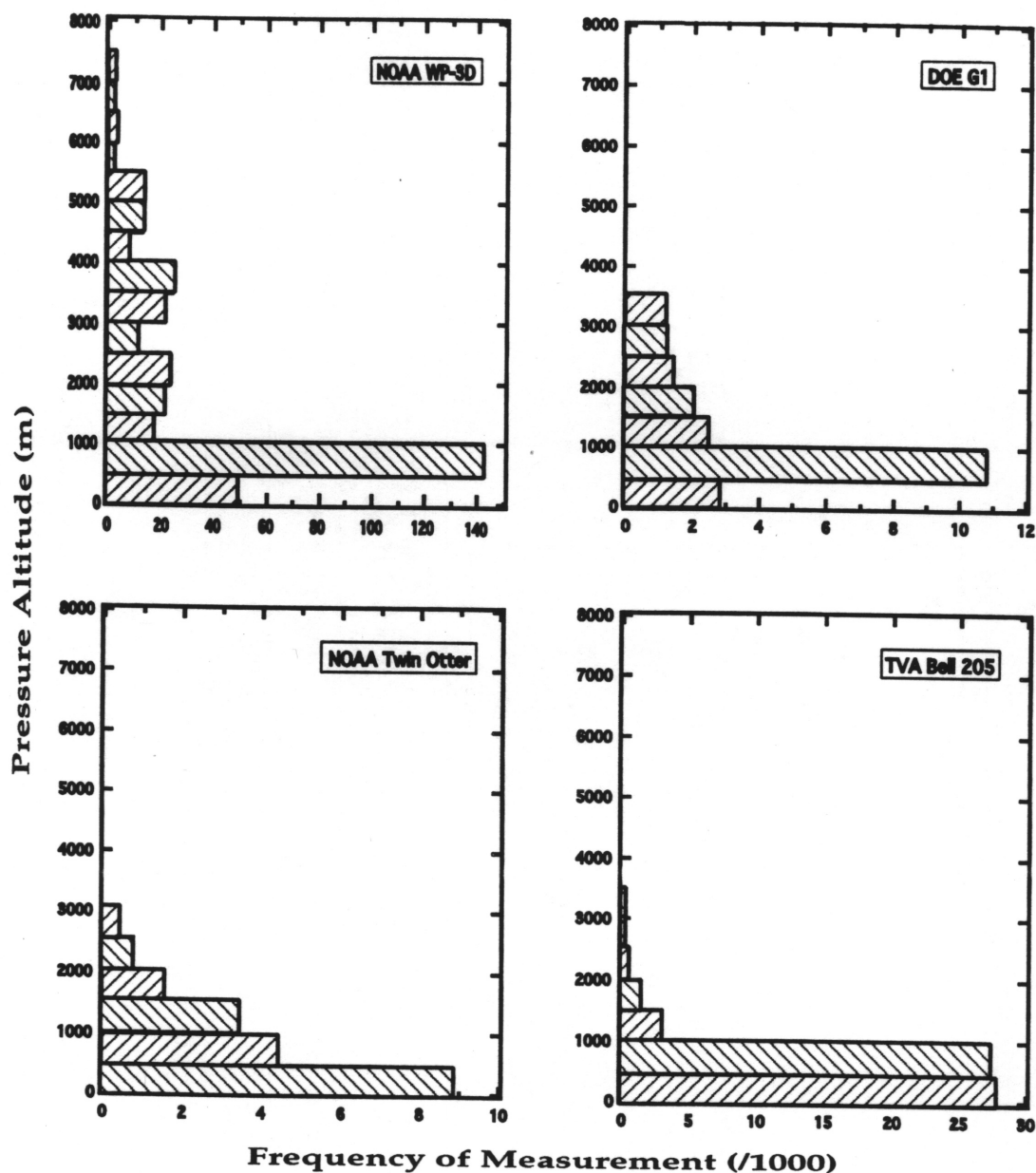


Figure 2. Measurement frequency distribution versus altitude for all the flights of the NOAA WP-3D, DOE G1, NOAA Twin Otter, and TVA Bell 205 Helicopter.

ozone and ozone precursors were identified and placed within the framework of wider subregional and regional surveys. All of this is described in detail in the following manuscripts.

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